Optimized synergy in networked infrastructure deployment and maintenance

Optimizing the planning of infrastructure works and the synergies in the trench.

Jonathan Spruytte, Mathieu Tahon, Koen Casier, Sofie Verbrugge, Didier Colle, Mario Pickavet

Ghent University – iMinds
Internet Based Communication Networks and Services research group (IBCN)
Gaston Crommenlaan 8 bus 201, B-9050 Gent, Belgium

Email: jonathan.spruytte@intec.ugent.be

Abstract

Underground infrastructure installation is prevalent in Belgium and both maintenance and new installations will lead to large costs. Important reductions in these costs are possible by performing road works in synergy. Formerly the overhead of the cooperation and the limited IT tools and data available limited the operators view on possible synergies and made at the same time exploiting these synergies less obvious and more cumbersome. With the increase of detail in the geographical information bases containing all information on the installation per operator, synergies open up more opportunities and could lead to very important reductions in the operators' costs. In order to reap these benefits, a set of challenges should be overcome. This paper indicates how optimization tools on trench structure and GIS planning can aid in exploring this potential. The first approach indicates how the trench can be optimally organized in order to reduce trench depth, width or overall costs. The second approach indicates how existing planning of road works of several infrastructure owners can be mapped to each other. The planned road works can be rescheduled to optimize overlap between infrastructure owners and group smaller road works into larger chunks, still taking into account timing constraint initially set and keeping budget for each period under control. The combination of both optimizations will allow operators to optimally align their mid- and long-term planning and use an optimal trench, reducing costs. It also indicates which data should be shared and how the optimization should be performed.

Keywords: Network deployment, scheduling, infrastructure networks, synergies

1 Introduction

Infrastructure owners, such as electricity, sewage or road owners, have a continuous task of detecting, isolating and solving problems in their network, maintaining and updating the existing infrastructure and finally also extending their network to reach all customers. Whether the infrastructure consists of streets, sewage, water, electricity, telecom or any other infrastructure type, any deployment and/or maintenance requires large road works in which the accessibility to the streets is badly reduced for the period of the project. When none of these projects are aligned, this will lead to severe discomfort in the area and will also lead to repetitively touching the same street with large road works, in which each project could cause non-intentional collateral problems to other infrastructures. It is clear that aligning different projects of the different infrastructure owners to each other, offers opportunities for saving time in the works as well as money. The main effort of opening up the street is only taken once and as such also a large part of the cost. Next to saving money, aligning road works will also reduce a lot of the nuisance to the inhabitants. In order to achieve optimally cooperative projects, several constraints should be taken into account:

1. All infrastructure should be installed, moved, maintained conform to standardization and safety regulations (min. distance between infrastructures, depth, etc.). This means that the digging should be optimized taking all these constraints into account. Optimization of this digging should be aiming at a combination of project duration, project costs, complexity, etc.
2. The part each actor will pay in the cooperation should be strictly less than what he would pay when performing the project on his own. All actors should pay a part which is in clear relation to their share of the costs and constraints they put on the project. Only when this is smaller than the costs they would incur in performing the project on themselves, they will be willing to cooperate in this project.
3. Tackling a project at a certain point in time should be both feasible and advantageous for all actors involved in the cooperation. This means that an urgent project for an actor will not be postponed over a long time, as well as that an actor will not be rushed into cooperating in a project which was not on its priority list.

The approach taken in optimally aligning infrastructure projects of different infrastructure owners in regards to the set of constraints is twofold.
A first optimization will look for the most economic format of the trench in which the different infrastructures should be jointly installed as early stated in [1]. In this optimization various different objectives (e.g. minimal time, minimal nuisance, etc.) could be pursued at the same time and the final solution will be a tradeoff between the different alternative solutions found. Based on the actual installation situation, the costs can be estimated and split amongst the different actors involved. While this cost allocation can be used in handling the cooperation, it will also act as an additional constraint on the selection. A scenario, in which one actor is not paying less in the cooperative case than he would be when executing the project alone, is clearly a scenario which will not be executed in a cooperative setting.
A second optimization will align multiple scheduled projects in such a manner that an optimal gain of the cooperation can be attained. This scheduling takes as input the geographical information of various scheduled projects from the different infrastructure providers and metadata linked to these projects from which e.g. the

timing constraints, urgency, priority, maximum budget can be deduced. A heuristic scheduling algorithm uses this information with an aim to optimally schedule the previously unrelated per infrastructure owner projects into cooperative projects. This scheduling has both a view on network – overlapping in location – as on timing – overlapping in execution time – level. Again multiple objectives, such as the total cost, overall nuisance to the inhabitants, regional spread, etc. are used. The constraints on timing, budget, network, etc. are translated into constraints for this optimization. The paper is structured around these two optimizations. The next section will propose an algorithm for optimally placing of the underground infrastructures. Section 3 will detail how the planning of road works of several infrastructure owners can be reschedule to align more works and gain by performing them in synergy. Section 4 concludes this paper.

2 Optimally aligning infrastructures in a trench installation

To indicate the possible synergies in the infrastructure rollout phase, the typical characteristics of each considered network must be taken into account. Typically in a fully buried installation, the following networks can be found underground: telecom networks (cable, copper and fiber), energy networks (electricity, gas and heat), drinking water and the sewage system. An overview of a typical cross-section of a road can be found in Figure 1.

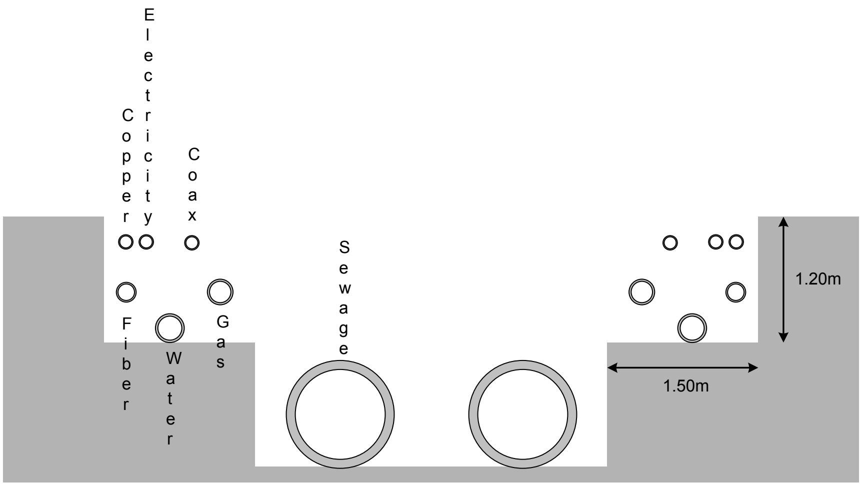


Figure 1 : cross section of a typical road

Since the liberalization of the energy market through the different energy packages, the energy network infrastructure falls under the responsibility of the transport and distribution system operators as stated in [2]. A typical electricity distribution network can be found at a minimal depth of 60 cm. Electricity cables are quite flexible and no strict safety regulations apply. For example, the minimal distance between an electricity cable and another network should only be 6 cm.

Gas networks require a more rigid duct system, mainly for safety reasons. In addition, a safety distance needs to be taken into account when installing other networks in the proximity of gas pipes. They are typically also installed deeper underground than electricity networks and no other infrastructure can be placed on top or below this network.

Telecom networks, typically the hybrid fiber coax (HFC), copper and fiber network, in a fully buried network, has no strict constraint in the underground location. At regular distances, flexibility points like manholes and street cabinets are installed. The last two networks considered are the drinking water and sewage system. Like the gas infrastructure, drinking water makes use of a rigid infrastructure and has similar safety requirements. Sewer systems are typically installed in the middle of the road, not in proximity to any other infrastructure and are as such not a likely candidate for synergy in installation.

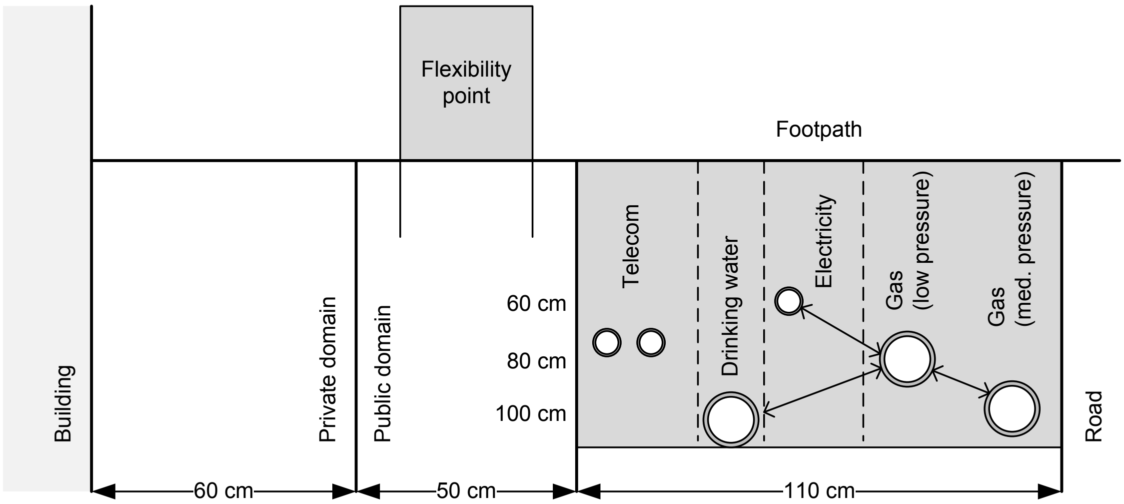


Figure 2: standard trench description

Table 1: Proposed standard trench parameters

Infrastructure type	Depth (m)	Distance to wall of trench (m)	Distance to other cables (m)
Electricity	0.6	0.05	0.06
Gas – low pressure	0.8	0.1	0.2
Gas – medium pressure	1	0.1	0.2
Telecom	0.75	0.05	0
Drinking water	1.10	0.1	0.2

The standard trench proposed by Eandis in [3], a Belgian electricity distribution system owner offers a first guideline towards a theoretical optimized trench, but in practice, rolling out a new network will probably not be executed in a Greenfield situation. The location of existing infrastructures and space limitations should all be taken into account. Therefore an optimization model in java code was constructed. When developing the model, two challenges were encountered.

The first challenge is identifying the parameter or function to optimize. The distribution net operator indicated both width and depth of the trench as important drivers for the total cost of the infrastructure deployment. This is reflected in the cost for opening and repairing the pavement (surface dependent) and the cost for digging (depth dependent). In this model, the total volume of the trench is optimized to minimize costs. However, the model can easily switch to other functions to optimize. The total width of the trench could be a more important factor, for example if the repair cost of the surface is very high. Other functions can easily be added to the model.

A second challenge towards the implementation of an optimization algorithm is the presence of distance constraints between different infrastructures. Since in most cases, only up to 6 infrastructures are present in one trench, computation time is not an issue. For each permutation, the first infrastructure is placed based on its safety constraints in the upper left corner of the available area (Figure 3). Each additional infrastructure is then placed on the lowest cost location of the remaining area. In this model, this is the position where the total volume of the resulting trench is minimal. As can be seen in Figure 3, electricity is placed in the upper left corner of the available area. Adding the constraints for the fiber network diminishes the available installation area. The model returns the optimal location of each infrastructure after checking every permutation. After identifying the optimal trench, the costs can be divided between the different utility owners.

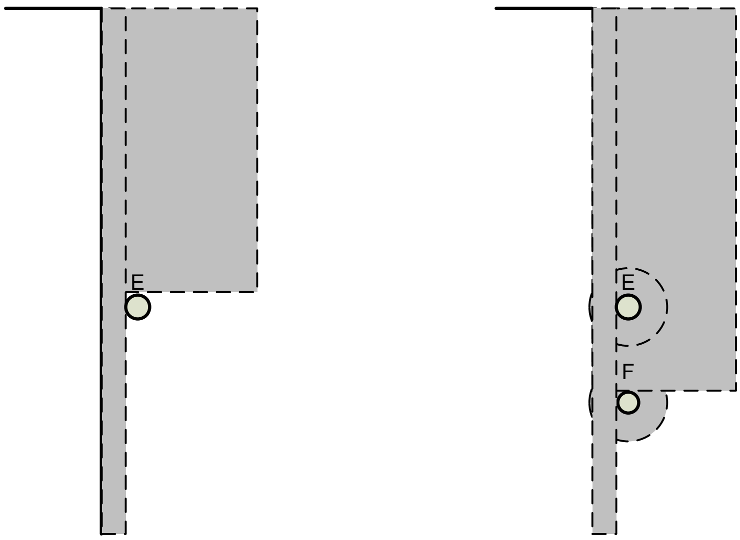


Figure 3 : Identifying the lowest cost location

In case each operator rolls out his network independently, every actor has to bear the costs of opening the pavement, digging the trench, installing of the cables or ducts and repairing pavement. Such a situation is presented in Figure 4 for electricity, fiber, gas and drinking water networks. In total, an independent rollout requires in the example case a total digging volume of just under $1.05m^2$ or $1.05m^3$ per meter installation. Table 2 summarizes the total costs per home passed (HP) for every utility provider. The impact of trench volume is clearly reflected in the digging costs, with the cost for drinking water 30% higher than for electricity. The extra cost for equipment only has a small impact on the installation cost.

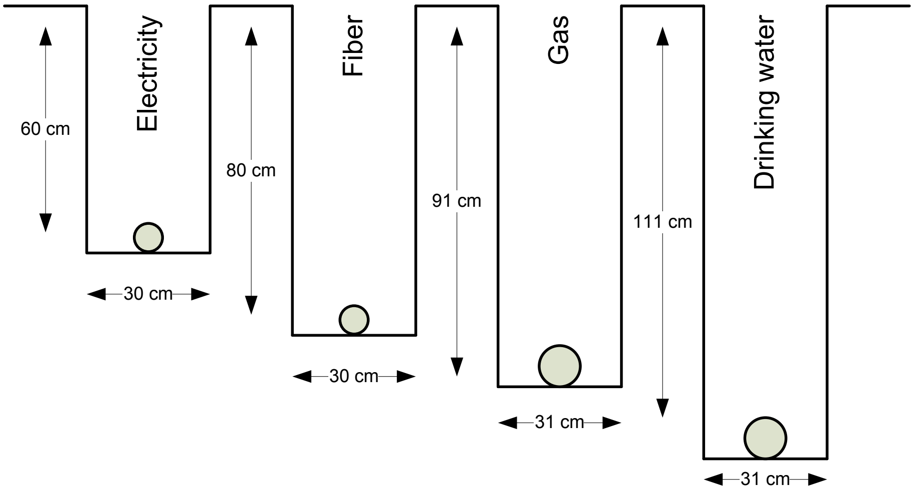


Figure 4 : Cross section of a stand alone rollout

Table 2 : Cost allocation results in the individual rollout scenario

	Electricity	Fiber	Gas	Drinking water
Digging cost	€82	€91	€98	€107
Installation cost	€113	€114	€117	€118
Equipment cost	€266	€265	€268	€268
Total cost	**€461**	**€470**	**€482**	**€493**

In the trench optimization model, energy (gas and electricity), drinking water and fiber networks are installed in synergy. Compared to the independent rollout, the total trench volume is reduced from $1.05m^2$ to $0.77\ m^2$. The synergy gains are considerable for all network operators, even when taking into account that digging is only part of the costs. The outcome of this installation is shown in Figure 5 and in Table 3.

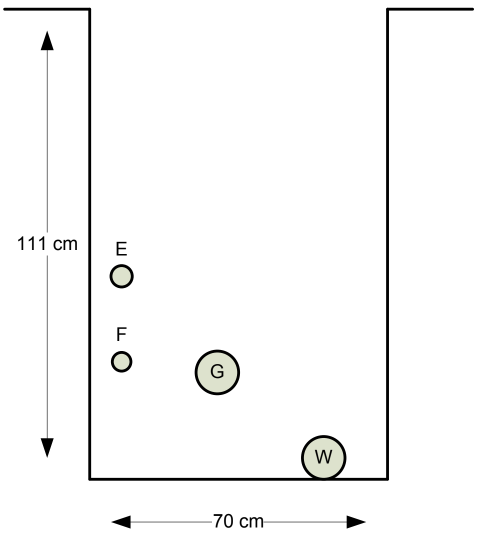


Figure 5 : Trench cross-section under greenfield rollout with all infrastructures

Table 3 : Cost results greenfield rollout

	Electricity	Fiber	Gas	Drinking water	Cooperation
Digging cost	€38	€42	€45	€49	€173
Installation cost	€90	€91	€93	€95	€369
Equipment cost	€266	€265	€268	€268	€1066
Total cost	**€393 (-15%)**	**€398 (-16%)**	**€406 (-15%)**	**€411 (-17%)**	**€1608 (-16%)**

Of course this algorithm can also be used in a more commons situation where brownfield installation is required, not all infrastructures are included and underground infrastructures are already in place and put additional constraints on the new installation. As an example of the best possible synergy, we show the optimal trench for the combination of electricity and communication networks as these pose little to no constraints.

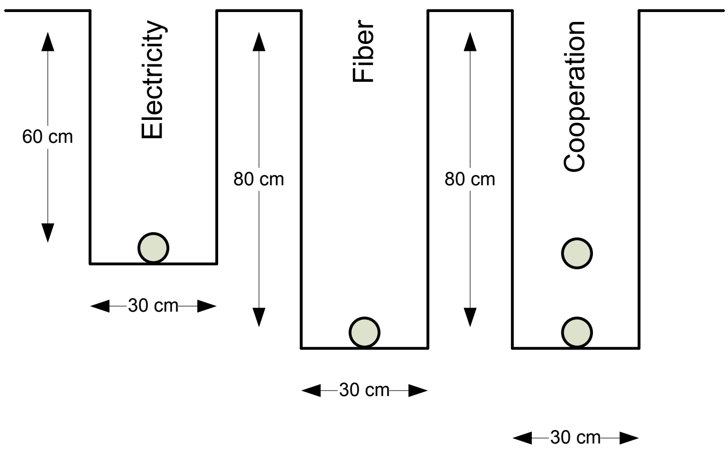


Figure 6 : Electricity - fiber cooperation cross-section

The impact on the total cost per HP is shown in Figure 6 and in Table 4. First, there is a major reduction in the total digging costs of 50%. This reduction, as already indicated, is driven by the large reduction in total digging volume compared with the independent rollout. Secondly, there is also a reduction in installation cost caused by the reduction in manpower for the opening and repair of the pavement. The cost reduction resulting from the cooperation is sufficiently large to benefit the business case for each utility provider.

Table 4 : Cost impact of cooperation during electricty and fiber network rollout

	Electricity	Fiber	Cooperation
Digging cost	€43	€48	€91
Installation cost	€86	€87	€173
Equipment cost	€266	€265	€531
Total cost	**€395 (-14%)**	**€400 (-15%)**	**€795 (-15%)**

3 Optimally scheduling infrastructure works

Clearly an installation in synergy promises to reduce the per infrastructure owner cost significantly, still many road works do not overlap. Infrastructure owners typically have a planning stretching multiple years, translating into working budgets based on strategic goals. Changing this on per synergy case is possible, but typically cumbersome and it might even lead to only marginally more joint installations. A better approach is to take a multi-period planning of each of the infrastructure owners together and try to find up-front an installation planning which will fit the strategic goals and budget constraints and at the same optimize the synergy gains.

As a motivation of this approach, we build a proof of concept scheduler capable of suggesting an optimized planning or road works for several infrastructure owners, when presented with a GIS description of these road works containing information on preferred period of planning and constraints on shifting in time per road work. This optimization approach looks for the best possible solution amongst a huge set of alternatives in which the overall cost function of the different infrastructure owners is optimized within the set constraints.

The problem and solution will be proposed in the following subsections. The first subsection describes how a base case (or a set of base cases) is constructed automatically conform to the problem statement and with full control over the size and complexity of the problem. This serves as a solid basis for testing the working of the genetic algorithm in outcome, detail as well as scalability. The second subsection describes how the genetic algorithm is constructed and how the cost function used for comparing alternative solutions is gradually refined to match the set goal of optimal synergies within strategic and budgetary constraints. Finally in the last subsection a clear overview of the results is presented and analyzed, while tradeoffs of the parameters in the solution as well as future extensions are discussed additionally.

3.1 Description of the problem base case

The optimal planning heuristic requires detailed data on the planned road works of at least two infrastructure owners for many subareas in a large area in a geographical information system (GIS) data format. The data from these infrastructure works of the different infrastructure owners should overlap both in area and in expected timing of the works in order to be useful for the scheduling algorithm. This data is often seen as quite confidential and is as such not easily shared with research partners containing all details and spanning a large area, especially not to be included in a publication.

Still we can work with fictitious data generated for training our algorithms. This fictitious data is generated by overlaying a grid over GIS information downloaded from OpenStreetMap[4]. In this particular case the street topology for an area within the city of Ghent has been used. Using this grid we get a set of squares, each containing streets for which we can schedule work. For instance a 10 by 10 grid will lead to 100 squares (wrapping some streets). By attaching a random timing range – a random start and end year (which can be the same)which is the preferably time range to schedule road works in this square of streets – to each square and for each infrastructure owner separately, we get an input for our scheduling optimization algorithm. To better reflect reality, we randomly selected only a part (e.g. 50%) of the squares for road works for each infrastructure owner, in which there is no correlation between these initial schedules for the two infrastructure owners. Furthermore, by making different grids for each infrastructure owner, some squares will overlap completely, while others only overlap partly.

With this generator we can generate base cases for the calculations. The overall base case which is used throughout further explanations is generated with two infrastructure owners, a grid of 30 x 5 over an area in Ghent where randomly 50% of the areas have been included as road works to be scheduled within the time period of 2014 till 2018. Figure 7 gives an overview of the base characteristics of such random planning. This base case clearly shows very little overlap of road works, and can be optimized to reduce costs by rescheduling road works to overlap as much as possible. At this point only 4% of the area installations can be performed in synergy and only 9% of the road works are clustered.

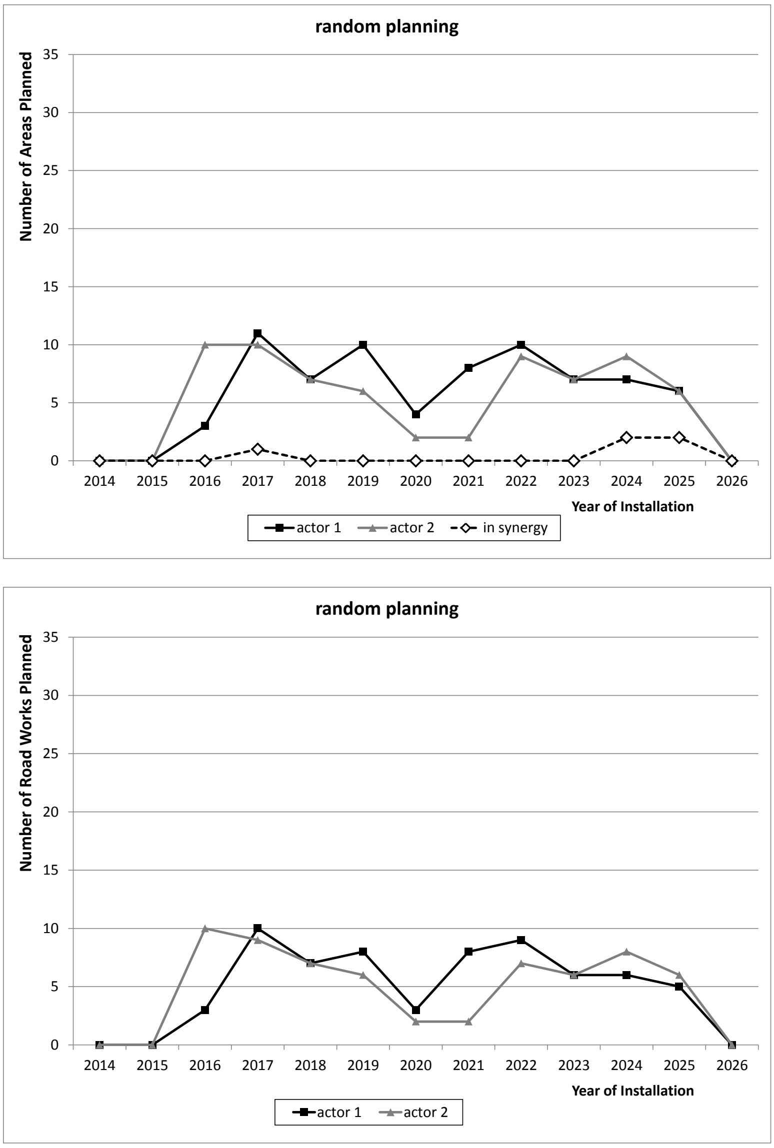
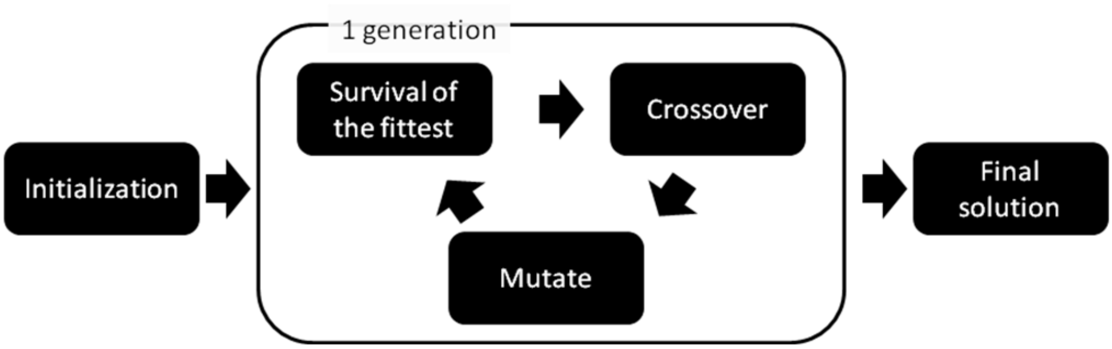


Figure 7: randomly planned installation areas for two operators used as input with indication of the existing possibilities for synergies

3.2 Construction of the genetic algorithm

There is an enormous range of possible schedules for the given road works, too many to exhaustively explore in the search for the full optimal solution. Scheduling problems are NP hard, so while an exhaustive search might succeed in smaller problems, the calculation time will grow very fast for a growth of the problem space and quickly be practically incomputable in reasonable time. As such a heuristic search is required and we used a genetic algorithm approach. This kind of problem strongly relates to the task scheduling problem as stated in [5].

Genetic algorithms are an advanced kind of search algorithms, which use techniques found in natural evolution. Within the algorithm, the group of possible solutions (the population) evolves generation after generation, using three basic actions: survival of the fittest (selection), crossover and mutation. Selection ensures that the best solutions are selected to breed offspring (using crossover) and at the same time ensures that the worse solutions are removed from the population. Finally mutation slightly changes the solutions in an attempt to improve them.



One of the core elements of a genetic algorithm is the fitness function, which calculates a fitness value for each individual of the population. The fitness function is highly dependent on the problem. The better the fitness function reflects the actual problem and captures the intricacies of any side effects, the better the solution will fit the real optimal solution. In the following subsections we will detail the fitness function and relate this to real costs or undesirable side effects of the results.

Scheduling for maximal synergies in work timings

Clearly a better overlap of the road works can be achieved when the time of the scheduling of two works in the same area coincides. This means that the fitness function should increase with an overlap of road works. As the costs of the installation can decrease with up to a factor of 2 in this area, the fitness function will increase the value of this area with a factor of 2 as well. The outcome of this optimization is shown in Figure 8.At this point already 25% of all area installations are planned to be performed in synergy and 12% of all road works are clustered.

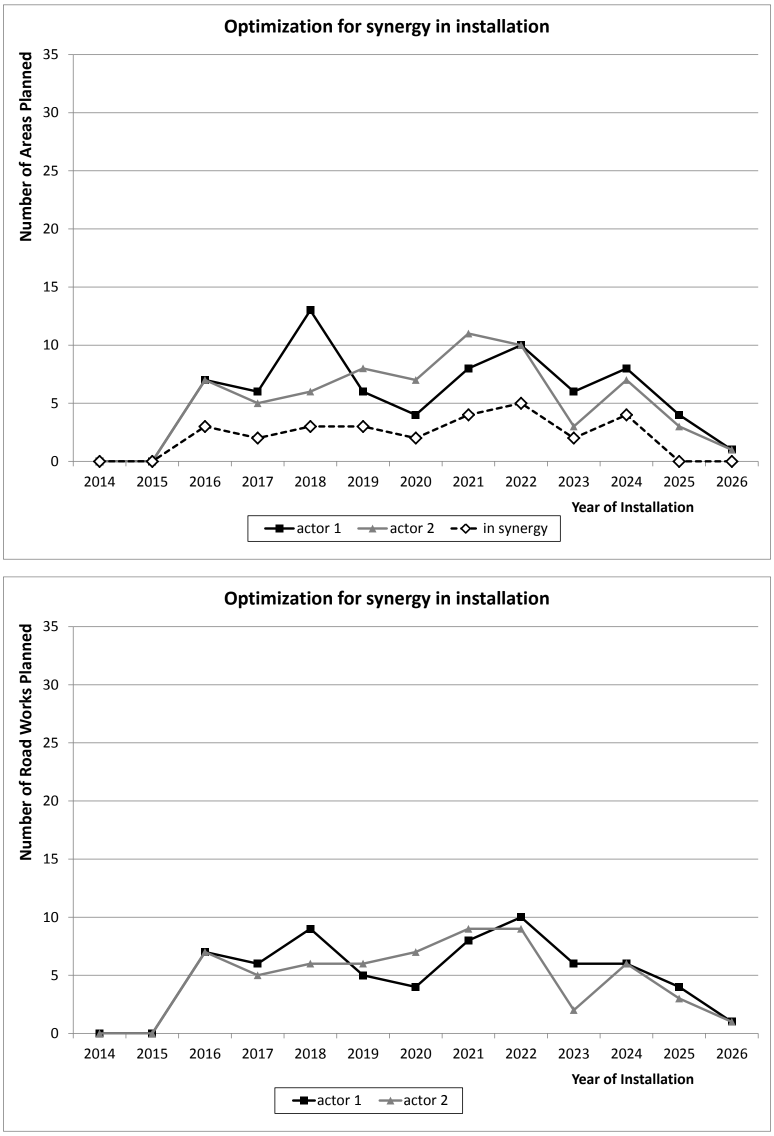
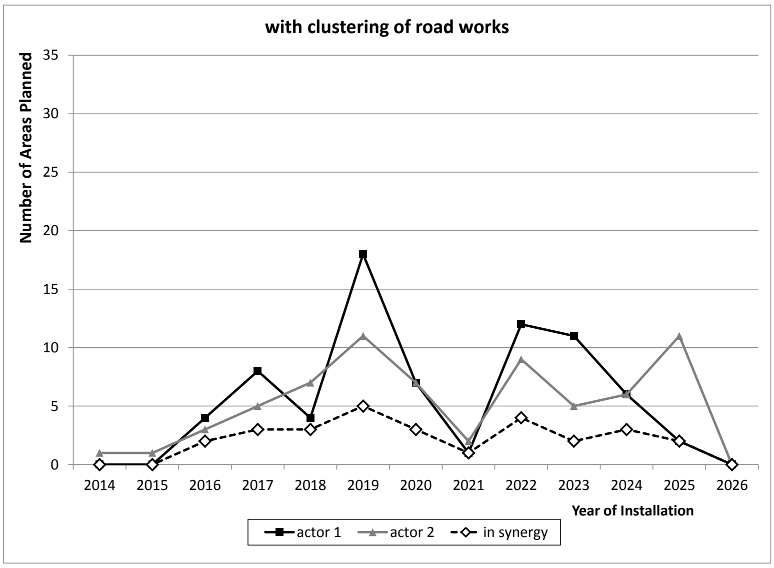


Figure 8: Results of the amount of areas and road works (clustering areas)planned per year for two operators with an optimization of the potential synergies Error! Reference source not found.

Clearly this optimization increases the amount of coinciding installation areas and will as such clearly decrease the final costs of the installation. The amount of clustered road works is quite similar to the amount of installation areas. Still more synergy gains are attainable when adjacent installation areas can be grouped into one larger road work in stretching a larger area.

Scheduling for maximal synergies in work locations

As mentioned before the coupling of several smaller conjoint road works into one larger road work will lead to better economies of scale and as such to potential gains. These are translated into the fitness function by increasing the value of conjoint areas. To do so, for each square a number of adjacent squares are analyzed. For these results, only the square one row up and the square one column to the right are considered, The outcome of the optimization using this new fitness function is shown in Figure 9.At this point still 25% of all area installations are planned in synergy and over 65% of all road works are clustered.



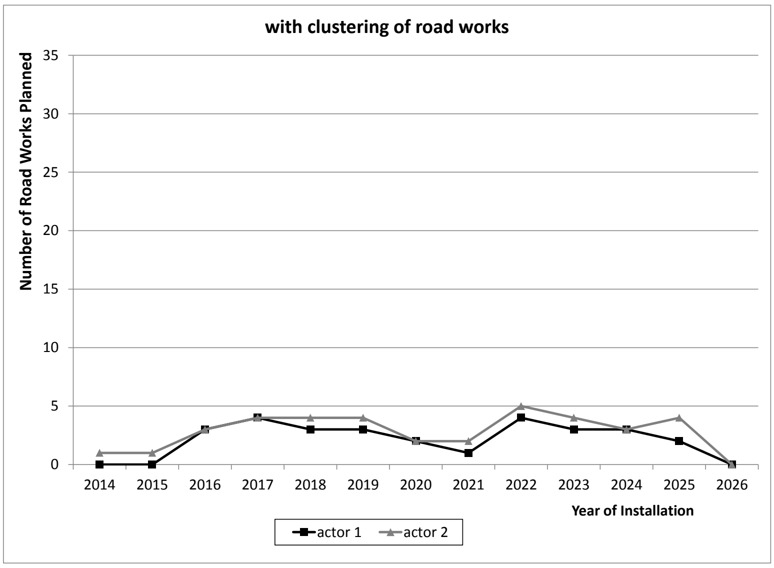


Figure 9: Results of the amount of areas and road works (clustering areas) planned per year for two operators with an optimization of the potential synergies and clustering

Clearly now road works are grouped nicely in large chunks of work leading to better gains in synergies as well as in economies of scale. Now a negative side effect of the scheduling becomes clear, as many of the scheduled road works are scheduled too far from their initial scheduling date. As the scheduling date could be driven by expected problems, required maintenance schedules or other constraints, this rescheduling could lead to new problems.

Considering timing constraints of the separate road works

In order to be more faithful to the original schedule for each road work, we add a term to the fitness function reflecting the measure in which a road work follows the initial schedule. For each period a road work is executed too early or too late a penalty is deducted from the fitness function. The outcome of this optimization is shown in Figure 10. At this point still 25% of all area installations are planned in synergy and still almost 35% of all road works are clustered.

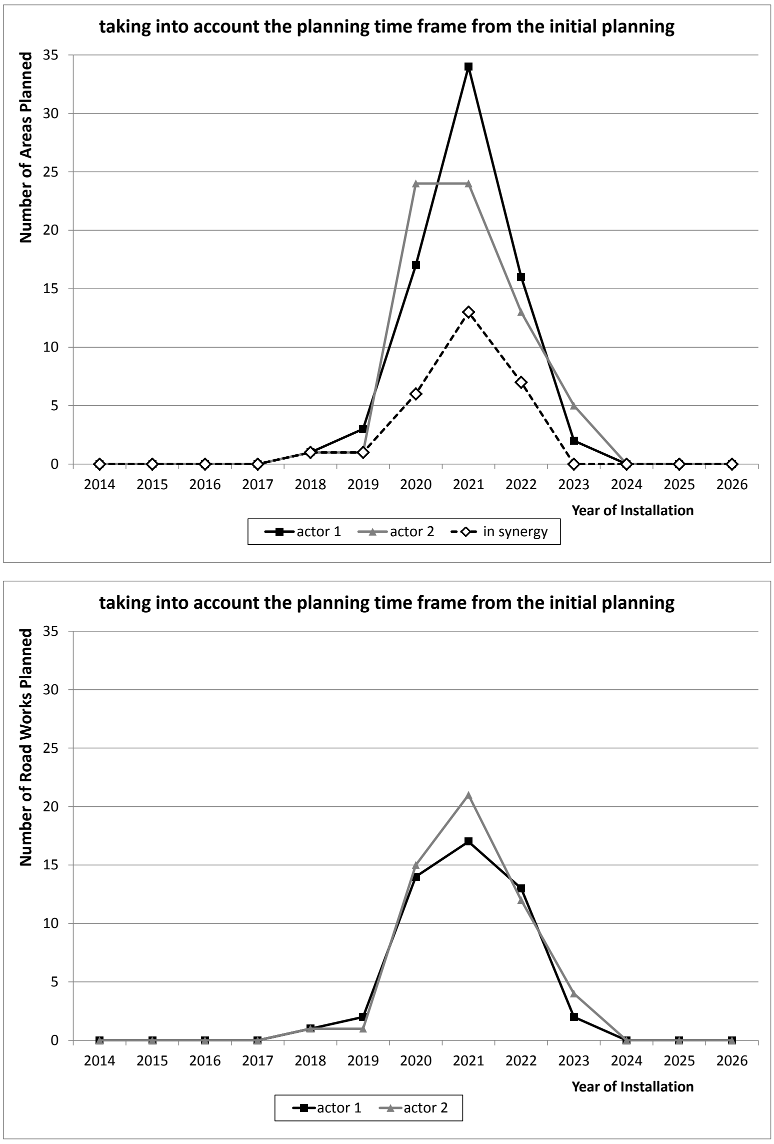


Figure 10: Results of the amount of areas and road works (clustering areas) planned per year for two operators with an optimization of the potential synergies and clustering taking into account the planning constraints Error! Reference source not found.

This optimization is combining both the optimized synergies; optimal grouping of road works and at the same time does not reschedule road works too much in time. The scheduling, however, shows a bumpy work schedule with too many road works scheduled in the same period leaving the other periods considerably less packed. This could lead to budgeting problems and infeasible planning schedules, manpower wise.

Considering the maximal work load of the infrastructure owner

To remedy the over and under-spending in the scheduled road works, we add a soft or hard(current) limit to the amount of road works which could reflect the effect of a budget constraint. The difference between a soft and a hard constraint in this is the size a budget breach will impact the fitness function. The outcome of this final optimization is shown in Figure 11.At this point still 25% of all area installations are planned in synergy and almost 30% of all road works are clustered.

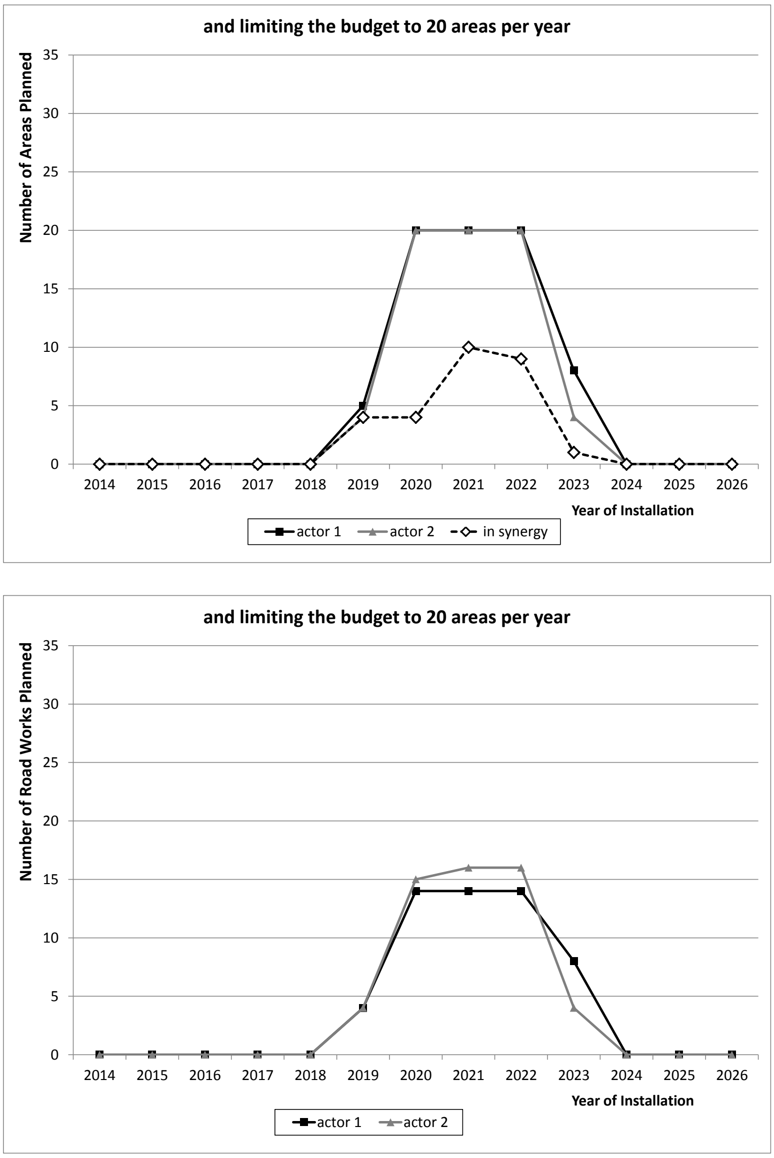


Figure 11: Results of the amount of areas and road works (clustering areas) planned per year for two operators with an optimization of the potential synergies and clustering taking into account the planning and budget constraints

4 Conclusions and future work

Underground infrastructures are prevalent in Belgium for conveying gas, water, electricity or telecom signals. Installation and maintenance of underground infrastructure is very expensive partly due to the digging of the trench. Performing this underground installation in synergy between different infrastructure owners can offer important economic gains.

This paper presented an algorithm for optimal placement of several underground infrastructures in synergy, in which all constraints of the different infrastructures are taken into account. This algorithm clearly shows that trenching costs can be reduced in optimal circumstances by up to 50%, leading to an overall reduction of 15% for a full infrastructure installation taking into account equipment and installation next to the trenching. Next to economic savings, synergies also open up additional benefits such as nuisance reduction by a shorter installation time, risk reduction, etc.

Clearly synergies can save a lot in the trenching costs and should be strived for. Still the infrastructure owners only consult each other on a relatively short term of their next installations and the fixed planning and budgets of other infrastructure owners do not easily allow changing plans on short term and cooperating in this potential synergy. This paper presented a heuristic algorithm for aligning the planned road works of two (or more) infrastructure owners with the aim to increase the potential synergies by smart rescheduling of the planned road works. This approach looks for overlapping and/or adjacent road works and tries to schedule them at the same time. Rescheduling is performed within the constraints of maximal yearly budget and maximal time shifting of each individual road work. The outcome of the rescheduling shows that potential synergies can be increased from 4% where road works are accidentally initially planned at the same time up to 25% in the optimal planning. The planning can even be more optimized by clustering road works with 30% and up to 65% less road works, allowing for considerably more economies of scale. The proposed fitness function for this genetic algorithm currently uses a point-based system to evaluate solutions. In the future this fitness function can be improved by using actual costs or by using a multi-objective approach. Using a multi-objective optimization, extra parameters like nuisance for inhabitants or the logically scheduling of zones – so optimal accessibility trough the city can assured – can be included.

This paper only presents a starting point, as synergies can provide important cost savings to the infrastructure owners. Future work will focus on rescheduling larger areas and more operators at the same time. In future implementations, the costs of installation and estimation of synergy gains should be estimated using the optimal trenching approach while other parameters like nuisance will also be part of the optimization.

Acknowledgements

A lot of information and knowledge applied in this work was gathered within the scope of ICON – TERRAIN project.

References

[1] Tahon, M., et al. Improving the FTTH business case - A joint telco-utility network rollout model. Telecommunications Policy (2013), http://dx.doi.org/10.1016/j.telpol.2013.01.004

[2] European Commission, Publications Office (2010). A digital agenda for Europe. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle: A+Digital+Agenda+for+Europe#0S

[3] Eandis (2010). Technical specifications for the installation of underground pipes. http://www.eandis.be/eandis/leverancier/l_soorten_werken.htm

[4] Openstreetmap.org

[5] Fatma A. Omara, Mona M. Arafa, Genetic algorithms for task scheduling problem, Journal of Parallel and Distributed Computing, Volume 70, Issue 1, January 2010, Pages 13-22, ISSN 0743-7315, http://dx.doi.org/10.1016/j.jpdc.2009.09.009.